



Deformation Analysis of Surface Crack in Rolling and Wire Drawing*

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The surface flaw of a drawn wire has a significant influence on the quality of a product. High-surface-quality drawn wires and rods have been required for the manufacture of automobiles and machines. Wire breaks due to large surface defects are common problems in wire drawing. The authors carried out rolling and multi-pass drawing of a stainless-steel wire with an artificial scratch, and investigated the growth and disappearance of a scratch from both sides by experiments and Finite Element Analysis (FEA). When the scratch angle is small, the scratch side surfaces are pushed toward each other and the scratch becomes an overlap defect. In contrast, when the scratch angle is large, the bottom of the scratch rises, and the scratch is recovered satisfactorily. Furthermore, the scratch shape and the drawing conditions were varied, and the deformation state of a scratch was clarified.

Key Words: Surface Defect, FE-Simulation, Wire Drawing, Wire Bar Rolling

1. Introduction

Recently, requirements concerning the surface quality of wires used for springs in automobiles have become more stringent (Fig. 1). Improvement of surface property is an important issue, since it has a significant effect on fatigue characteristics⁽¹⁾. There is also the problem that the limiting upsetting ratio decreases as a result of the generation of surface flaws, as shown in Fig. 2, on the wire rod during cold forging of bolt heads⁽²⁾⁻⁽⁴⁾.

The causes of surface flaws of wire have been discussed at the production sites, but many issues still remain unsolved. How the surface flaws created before machining develop or disappear after machining has not yet been clarified. In general, wires are produced by multiple rolling and drawing processes. Some researchers have carried out experimental studies of surface flaws during rolling of a wire rod, although such studies are few in number^{(5),(6)}.

However, there is no report of Finite Element Analysis (FEA) of a rolling of a rod and bar with surface flaws, since (1) the deformation analysis of flaws during

rod rolling is more complicated than that of a plate, (2) the size of flaws is extremely small compared with that of the wire and (3) the analysis requires a three-dimensional (3-D) FEA. In addition, the number of reports, including our reports^{(7),(8)}, on surface flaws during drawing, which precedes rolling, is still small. In this study, the growth and disappearance of surface scratches are examined by applying 3-D FEA to (1) the analysis of billet rod rolling, where scratches are artificially made on the billet surface and (2) the drawing experiment and analysis using wires with artificially made scratches on the surface. On the basis of the results obtained, the possibility of recovering surface

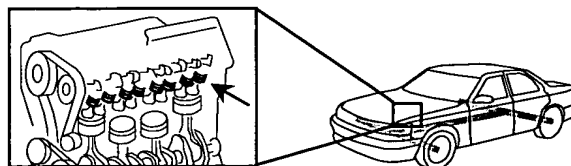


Fig. 1 High quality spring for automobile

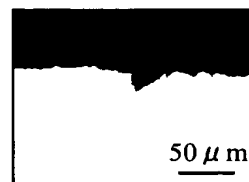


Fig. 2 Actual cracks on surface of wire rod in plant

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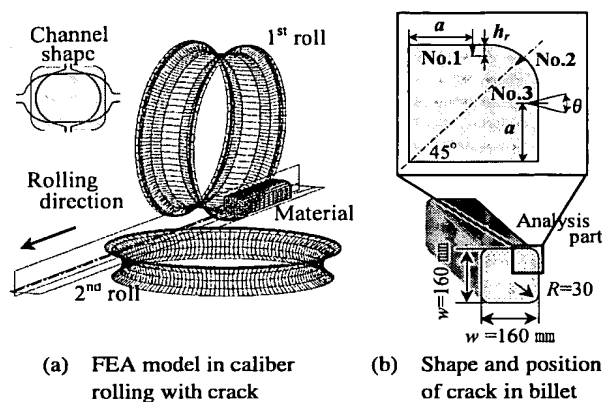


Fig. 3 FEA model of caliber rolling with scratch and position of crack in billet

defects by means of rolling and drawing is examined by both FEA and experiment.

2. FEA Model, and Rolling and Drawing Experiments

The materials used in this experiment and analysis were stainless steel rods (SUS304), the characteristics of which are not easily affected by their metallic structure. Scratches were artificially created on the billet and wire rod.

2.1 Analysis of rolling using billets with scratch on the surface

Using commercially available 3-D FEA codes MSC MARC 2003, analysis of grooved rolling using a billet with surface scratch, as shown in Fig. 3(a), was carried out. To shorten the calculation time, the size of the model was 1/4 that of the original. Hexahedron meshes are used in this FE analysis. Steel wire rods are generally finished by rolling for approximately 4–10 passes; however, in this analysis, rolling comprising two passes, i.e., square→oval→round, was adopted since the initial deformation of scratches was focused on.

The shape of the billet, rolling schedule and groove shape of the roll were identical to those used in an actual factory. The rolling was carried out by the horizontal–vertical (H-V) method, and one-pass reduction was approximately 20%. The shape of the billet is shown in Fig. 3(b). The dimensions of the billet were $w = 160$ mm and $R = 30$ mm. In an actual situation, there are various scratch shapes; in this study, the scratch was assumed to be V-shaped. Since scratches are frequently observed at the corners of material surface, scratches were made at three positions: the upper side of a corner, on the corner and below the corner (on the side surface) (Fig. 3(b)).

The ratio of the size of the scratch to that of the billet was 3%, and the parameters of the scratch were $h_r = 4.8$ mm, $a = 40$ mm and $\theta = 30^\circ$. The scratch at the up-

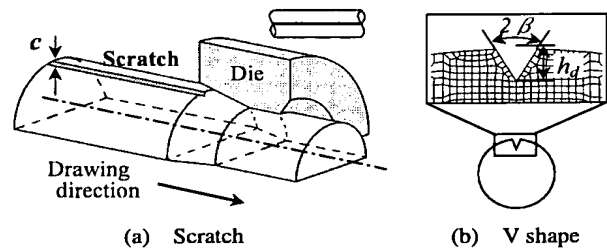


Fig. 4 Drawing model with scratch on wire surface for FEA

per side of the corner was denoted No.1, that on the corner No.2 and that on the side surface No.3. In actual operation, such large scratches are rarely observed; the scratch size ratio of 3% was assumed to clarify the deformation of fundamental scratches.

2.2 Drawing experiment and analysis of scratches

The scratches were artificially made in the axial direction on the surface of the wire, as shown in Fig. 4. The scratch was V-shaped to represent the scratches observed in actual manufacturing. The wire diameter was 10 mm, and the scratch depth was $h_d = 0.3$ mm, which was 3% of the wire diameter. The die half-angles were $\alpha = 6^\circ$ (frequently adopted in an actual factory) and $\alpha = 13^\circ$ to examine the effect of change in the die half-angle on the behavior of scratches. One-pass reduction was $R/P = 10$, 20 or 30%. Commercially available sodium stearate soap was used as lubricant. The results of analysis by FEA were compared with those obtained experimentally.

3. Result and Discussions

3.1 Deformation of surface scratch in rolling

3.1.1 Deformation analysis of scratches during rolling Figure 5 shows the change in the shape of artificial V-shaped scratches created ($h = 4.8$ mm, $\theta = 30^\circ$, as shown in Fig. 3) on a square billet subjected to one-pass rolling (oval). The scratches started to close from the bottom of the scratch regardless of the position on the surface (Nos.1–3); it is confirmed that the scratch is basically closed after one-pass rolling. Since rolling produces concave contact between the roll and the material, the corners of the material first come into contact with the roll. Therefore, the deformation velocity differs at each position; the shape of the closed scratches is slightly curved.

When round to round drawing is carried out, since the wires are uniformly processed in both circumferential and radial directions, the size of scratches decreases while the original shape is maintained. However in the case of rolling, the shape of the scratch varies depending on several factors, such as scratch position and channel section on the roll, and it is difficult to trace back the original scratch shape from the scratch shape after rolling. In rolling, material extends in both the forward and width directions. Therefore, when there is a scratch

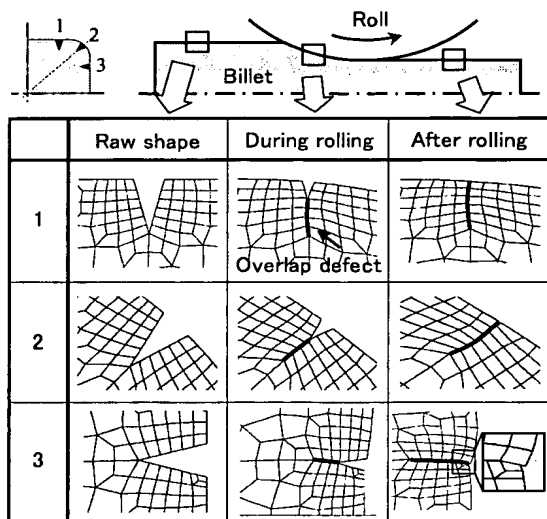


Fig. 5 Changes of crack shape during rolling

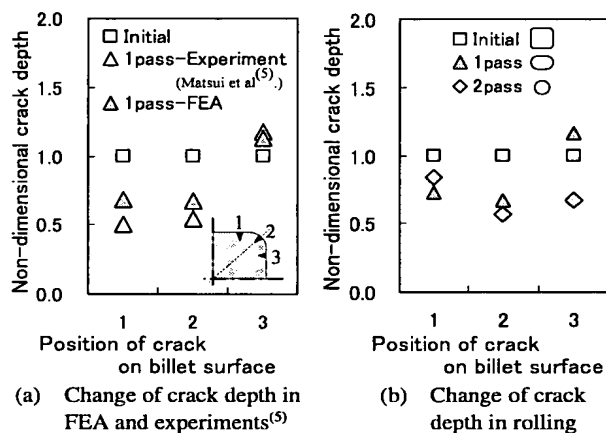
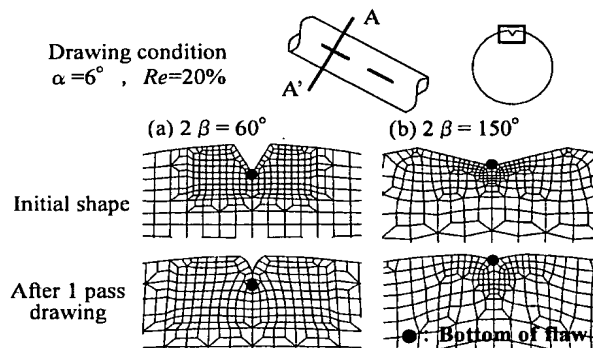


Fig. 6 Changes of depth of surface crack after rolling

with a wide opening on the side surface of the billet, as in this study, the extension of the upper side of the scratch in the scratch-width direction is greater than that of the lower side, and deformation proceeds as if the upper side of the scratch covers the lower side (square in Fig. 5).

Since the walls inside a scratch mechanically come into contact with each other, as explained above, the problems associated with scratches remain even after repeated rolling. In addition, the wire is subjected to hot rolling by which an oxide layer forms on the surface. It is natural to assume that the oxide layer remains inside the material after the scratches are closed.

3.1.2 Comparison of FEA and experimental results Figure 6(a) shows the change in the scratch depth after one-pass rolling, determined by FEA and experiment at an actual production site⁽⁵⁾. Although there are some differences between the two values, they show similar tendencies. Since scratches Nos.1 and 2, which come

Fig. 7 Change of scratch shape after drawing of wire with scratch which have various scratch angle 2β

directly into contact with the roll, are subjected to compressive strain, the scratch depth decreases; in contrast, for scratch No.3, which does not come into contact with the roll, the width of the scratch increases, and the scratch depth also increases compared to the scratch depth prior to the pass. Figure 6(b) shows the change in the scratch depth after two-pass rolling, determined by FEA. Since rolling is carried out by the H-V method, scratch No.1, which exists on the upper side during one-pass rolling, becomes a free surface (it does not come into contact with the roll) during the second pass. For this reason, the scratch depth after two passes is greater than that after one pass. In contrast, scratch No.2 comes into contact with the roll during both the first and second passes, and the scratch depth after two passes decreases compared to that after one pass. The depth of scratch No.3 significantly decreases after the second pass, since scratch No.3 comes into contact with the roll during the second pass.

3.2 Analysis of scratches on surface during drawing

It is extremely difficult to remove surface flaws of wire rods obtained by rolling at an actual production site. Flaws due to scratching and concave cracks due to shaving may be generated on the wire surfaces because of inappropriate handling during processes such as rolling, drawing and winding at an actual fabrication site. Among the various shapes of flaws, the deformation process of V-shaped scratches is examined by both FEA and experiment in this study.

3.2.1 Deformation analysis of V-shaped scratches

To examine the effect of the initial scratch angle on scratch growth, the initial scratch angle, 2β , of the V-shape scratch was varied. The proportion of scratch depth to wire diameter was constant at 3% (0.3 mm), while 2β was changed in the range of $60^\circ - 150^\circ$. The drawing conditions were $\alpha = 6^\circ$ and $R/P = 20\%$.

Figure 7 shows the initial scratch shape when 2β was 60° (Fig. 7 (a)) and 150° (Fig. 7 (b)), and the scratch shape after one-pass drawing determined by FEA. The black dot

in the figure indicates the bottom of the scratch. When 2β is small (Fig. 7(a)), since the outer diameter of the wire decreases during drawing, the wire is subjected to high pressure in the circumferential direction. Therefore, the width of the scratch decreases; however, at the bottom, the scratch becomes an overlap defect. In contrast, when 2β is large (Fig. 7(b)), the scratch recovers as the bottom of the scratch rises to the surface of the wire; therefore overlap defects do not occur. Two mechanisms of scratch recovering, i.e., rise of the bottom of the scratch and protrusion from the sides of the scratch, were confirmed.

3.2.2 Effect of die angle A scratch (initial depth $h_d = 0.3$ mm) was formed on a wire ($\phi 10$ mm) and wire drawing was analyzed with reduction R constant at 20% and die half-angle α either 6° or 13° , to examine the effect of the die half-angle on the growth and recover of scratches. The shape of the initial scratch is shown in Fig. 4.

Figure 8 shows the relationship between initial scratch angle 2β and scratch depth for two different die half-angles. With increasing initial scratch angle 2β , scratch depth becomes smaller. When 2β is small, the scratch easily becomes an overlap defect, leading to slow recover of the scratch. In contrast, when 2β is large, the bottom of the scratch rises and the scratch depth decreases. It is also confirmed that scratch depth is small with a large die half-angle ($\alpha = 13^\circ$). Figure 9 shows the flow of the wire when $\alpha = 6^\circ$ (Fig. 9(a)) and $\alpha = 13^\circ$ (Fig. 9(b)), as analyzed by FEA. As shown in Fig. 9, material flow at the

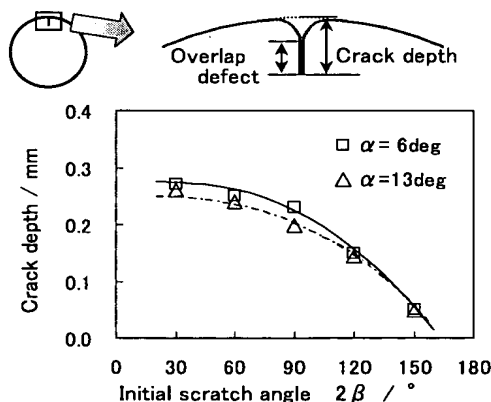


Fig. 8 Relationship between initial crack angle and crack depth after drawing

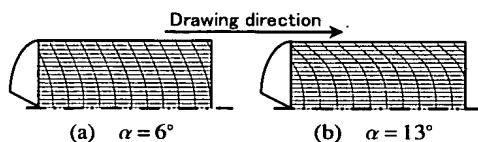


Fig. 9 Comparison of material flow between 6° and 13° die half-angle

surface of the wire when $\alpha = 13^\circ$ is more significant than that when $\alpha = 6^\circ$. Since the diameter of the wire decreases uniformly when $\alpha = 6^\circ$, the scratch also shrinks uniformly and becomes embedded in the material. However, when $\alpha = 13^\circ$, the material flow on the surface is extremely significant, the bottom of the scratch rises to the surface of the wire. For these reasons, it is considered that the scratch depth with $\alpha = 13^\circ$ is smaller than that with $\alpha = 6^\circ$.

Wires and rods are often subjected to cold forging after drawing, during which wire breakage occurs frequently because scratches exist on the surface. Wire breaks observed during cold forging largely depends on scratch depth⁽²⁾. Therefore, reducing the scratch depth to as small as possible is desirable.

3.2.3 Effect of reduction In order to examine the effect of the reduction of the deformation of scratches, drawing is carried out with die half-angle $\alpha = 6^\circ$, and one-pass reduction $R/P = 10\%$ (3 passes) or 28% (1 pass). The deformation of scratches is compared at total reduction $R_t = 28\%$, under two different one-pass reduction conditions. Figure 10 shows the results. A large difference in the manner of scratch closure is observed. When drawing is carried out for three passes with $R/P = 10\%$, the scratch essentially closes and the opening width is small. However, when drawing is carried out with $R/P = 28\%$, the scratch does not close to the same extent as that with $R/P = 10\%$, and the opening width is large. Similar results were obtained in the experiment. When R/P is high, material flows more easily in the axial direction, and the compressive stress in the circumferential direction, which is necessary to close scratches on the surface, decreases. In contrast, when R/P is small, the compressive stress in the circumferential direction increases, leading to a decrease in the opening width of the scratch.

Figure 11 shows the relationship between initial scratch angle 2β and overlap defect depth. As explained above, scratch depth varies during drawing depending on

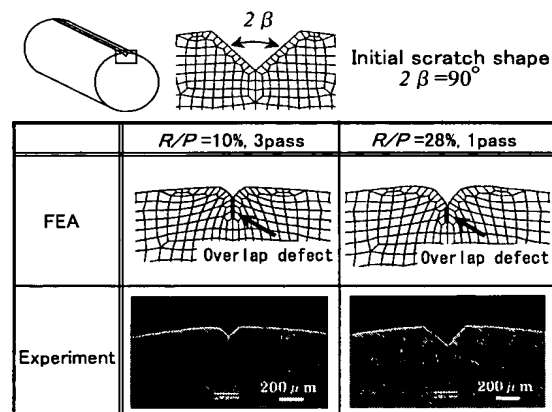


Fig. 10 Overlap state of crack after drawing ($R_t = 28\%$)

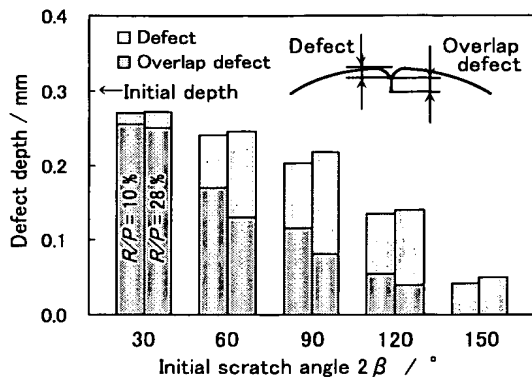


Fig. 11 Length of overlap and defect of crack after drawing

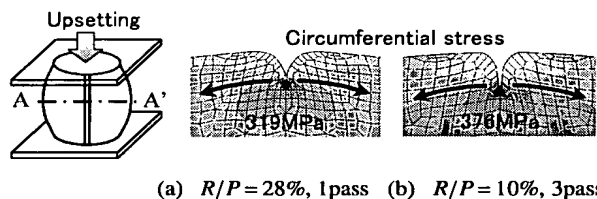


Fig. 12 Circumferential stress on cross-section A-A' during upsetting ($(h_0 - h_1)/h_0 = 20\%$)

the die half-angle. However, change of R/P has a negligible effect on scratch depth. The overlap defect depth is smaller with larger R/P , with any initial scratch angle. On the basis of the results in Figs. 10 and 11, under a large R/P condition, the overlap defect is short and the opening width is large.

3.2.4 Effect of scratch width on upsetting

Rods are frequently machined into screws and bolts after drawing, and scratches may occur during the fabrication of their heads. In upsetting tests carried out using wire rods with scratches on the surface, the limit compressive stress is higher in open scratches than in closed scratches⁽³⁾. Therefore, to examine the effect of the opening width of scratches during drawing, an upsetting test was carried out by FEA, using the two types of scratches shown in Fig. 10. The compression ratio was $(h_0 - h_1)/h_0 = 20\%$.

Figure 12 shows circumferential stress applied at the bottom of the scratch during upsetting. For both $R/P = 10\%$ and 28% , the inner walls of the overlap defect, which are merely in mechanical contact due to drawing, instantaneously separate. The circumferential stress at the bottom of the scratch is 319 MPa for $R/P = 28\%$, and 376 MPa for $R/P = 10\%$. A scratch which initially has a large opening is more resistant to spreading of the material in the circumferential direction during compression. When the opening width of the scratch is small, the bottom of the scratch is subjected to deformation which causes it to extend in the circumferential direction, leading to large stress. There is

a possibility of the scratch developing into a severe scratch that will lead to fracture of the material when the stress at the bottom is high. Therefore, it is desirable for the stress applied at the bottom of the scratch to be low.

On the basis of the results obtained, it is considered that the possibility of generating scratches observed in the forging process, which is carried out following drawing, can be reduced when drawing is carried out with a high R/P and a large opening width of the surface scratch.

4. Conclusions

Experiments and three-dimensional FEA of wire bar rolling and drawing of wire rods were carried out to examine the deformation behavior of scratches on the surface during these processes. We obtained the following conclusions.

(1) The deformation behavior of scratches after rolling and drawing was clarified by 3-D FEA of wires and rods with scratches on the surface. The FEA results were in fair agreement with the experimental results.

(2) Most of the V-shaped scratches developed into overlap defects after rolling. The scratch depth at a free surface, where the scratch does not come into contact with a roll, increases, whereas the scratch depth decreases when scratches come into contact with the roll and are subjected to compressive stress.

(3) When wires with scratches are drawn, many of the scratches develop into overlap defects at the bottom. However, when the initial scratch angle 2β is 150° or more, the bottom of the scratch rises and no overlap defects develop.

(4) The depth of the scratch can be reduced by drawing under high die half-angle and high reduction conditions; the overlap defect length can also be minimized.

(5) The effect of the opening width on the development of the scratch at the bottom was examined by performing upsetting analysis using wires and rods with scratches of the same depth.

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Effects of Inclusion on Die Contact Compressive Stress during Copper Shaped Wire Drawing by 2D FEA

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Abstract

The effects of inclusion size and length on copper shaped wire drawing were investigated. The deformations and the mean normal stress of copper shaped wires that contain an inclusion, were calculated by two-dimensional finite elemental analysis. The results, during drawing a wire containing an inclusion; necking occurred. The effects of inclusion size and length, on contact compressive stress during copper shaped wire drawing were carried out.

Keywords: Wire fracture, finite elemental analysis, copper shaped wire, inclusion, deformation, compressive stress, necking, die surface

Introduction

Extra fine wire processing requires a large number of drawing passes, and intermediate softening heat treatments (Yoshida 2000); however, in some cases, the fracture of wires occurs, resulting in high manufacturing costs. In particular, for wires with diameters of 0.1 mm or less, the product price increases exponentially with the decrease of wire diameter. The causes of wire fracture have been actively studied for a long time (Avitzur 1968). However, there are a few published reports.

Table 1 Material properties and drawing conditions used for FEA

	Copper (wire)	WC (inclusion)
Young's modulus E (MPa)	120000	1000000
Yield stress σ_y (MPa)	150	1000
Poisson's ratio ν	0.3	0.22
Die half-angle α (deg)	8	
Single reduction Re (%)	17.4	
Coefficient of friction μ	0.05	

Theoretical Wire Drawing Model Analysis

The wire drawing processes are classified as indirect compression processes, in which the major forming stress results from the compressive stresses, as a result of the direct tensile exerted in drawing (Mielnik 1991). The converging die surface in the form of a truncated cone is used. The analytical or mathematical solutions are obtained by the free-body equilibrium method. By totaling the forces in the wire drawing direction, of a freebody equilibrium diagram of an element, of the wire in the process of being reduced. Then combining the yield criterion with equation for the axial force, integrating the resulting differential equation, and simplifying, the equation for the average drawing stress is

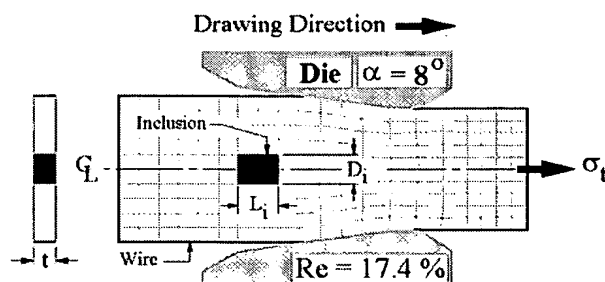


Fig. 1. The analytical model was used.

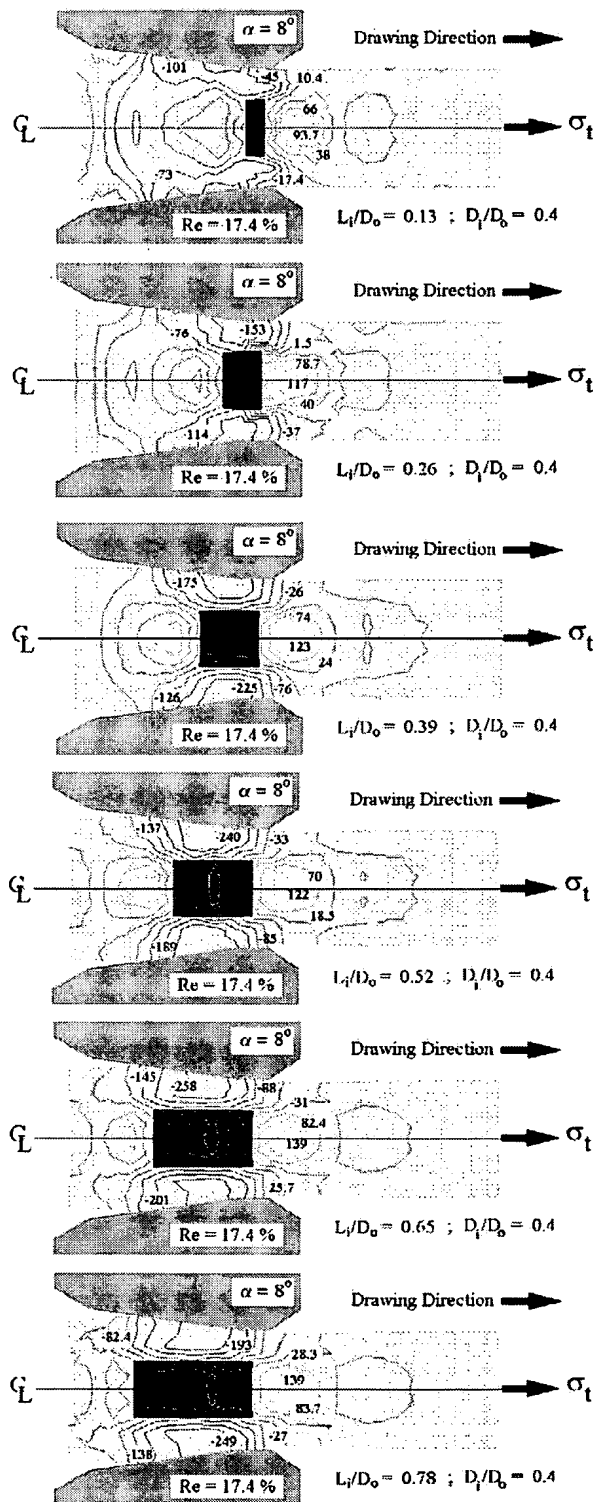


Fig. 2. The distributions of mean normal stress and deformation of copper shaped wires with a different length inclusion for inclusion size equal to 0.4 during wire drawing.

obtained. The derivation of this equation for drawing on a constant shear factor, neither a back pull stress, nor the redundant works were included. These terms may be added respectively, to give the equation for the front pull stress for drawing.

The above mentioned equations are only used for homogeneous wire drawing investigations. But non-homogeneous wire drawing, such as wire drawing that contains an inclusion, is a more complicated problem to investigate using those simple equations. In this case, the behaviors of wire drawing with an inclusion are easily investigated by two-dimensional FEA.

Optimal Die Half-Angle Experiment

The author and his colleague (Norasethasopon and Tangsri 2001) investigated the effects of die half-angle on drawing stress during wire drawing using the experiment to find out the optimal die half-angle of copper wire. The copper wires used as specimens have their properties as $E = 120000 \text{ MPa}$, $\sigma_Y = 150 \text{ MPa}$, and $\nu = 0.3$. They have a diameter of 5.5 mm. The reduction/pass of copper wire drawing was 17.4%, so that drawn wires have a diameter of 5 mm.

In this Experiment, the various die half-angles such as 4, 6, 8, 10, and 12° were used. The drawing stresses of copper wire during drawing at room temperature, versus the die half-angle, were obtained. For a die half-angle of 4°, the drawing stress was large. For the die half-angle of 6, 8, 10, and 12°, the drawing stress decreased as the die half-angle increased, until 8° approximately, and then increased as the die half-angle increased. The minimum drawing stress and the largest elongation were at a die half-angle of 8°. So that the optimal die half-angle, for copper wires drawing was approximately 8°.

FEA Results and Discussion

A two-dimensional finite element method was used to analyze the effect of an inclusion on copper shaped wire drawing. Fig. 1 shows

the analytical model used. The black part was an inclusion in a copper shaped wire. The inclusion was located at the center axis of copper shaped wire. The authors assumed that the inclusion was a sintered hard alloy (WC), and have the material properties and drawing conditions used in this analysis as shown in Table 1. The inclusion length was set to be L_i/D_0 , the ratio of inclusion length to dimension of wire cross section, and varied as 0.0, 0.26, 0.52, and 0.78. The inclusion size was set to be D_i/D_0 , the ratio of inclusion dimension to dimension of wire cross section, was varied as 0.0, 0.2, 0.4, and 0.6. The die half-angle (α), reduction of area (Re) and coefficient of friction (μ) were set at 8° , 17.4 %, and 0.05, respectively. The authors assumed that the inclusion and the copper matrix were joined at the boundary, and that the materials used were not work-hardened during the process. In this analysis, a wire was considered as a copper shaped wire, containing a hard inclusion subjected to steady deformation.

When the high compressive stress at the die contact surface during wire drawing occurred, the die contact worn surface easily occurred. The contact compressive stress ratio ($\sigma_{c,i}/\sigma_c$), the ratio of contact compressive stress at the die contact surface of wire containing an inclusion to compressive stress of wire without inclusion, as an inclusion passes through the

die was shown in Fig. 3. The L_i/D_0 slightly

influenced contact compressive stress on L_i/D_0 approximately up to 0.2. The contact compressive stress rapidly increases, as L_i/D_0 and D_i/D_0 increase, when L_i/D_0 was between 0.2 to 1.0. The contact compressive stress was not effected by inclusion length when L_i/D_0

was approximately greater than 1. But the inclusion size strongly influenced contact compressive stress, and it increased as inclusion size increased.

Conclusions

1. Necking occurred on the copper shaped wire surface in front of inclusion near inclusion boundary, and its magnitude increased as inclusion size and length increase.
2. The inclusion length slightly influenced contact compressive stresses for a wire that contains a short inclusion.
3. The inclusion length strongly influenced contact compressive stress.
4. In case of long inclusion, its length greater than 1.0, the inclusion size strongly and directly influenced on contact compressive stresses, but the contact compressive stresses were not effected by inclusion length.
5. Wire breakage occurred when inclusion

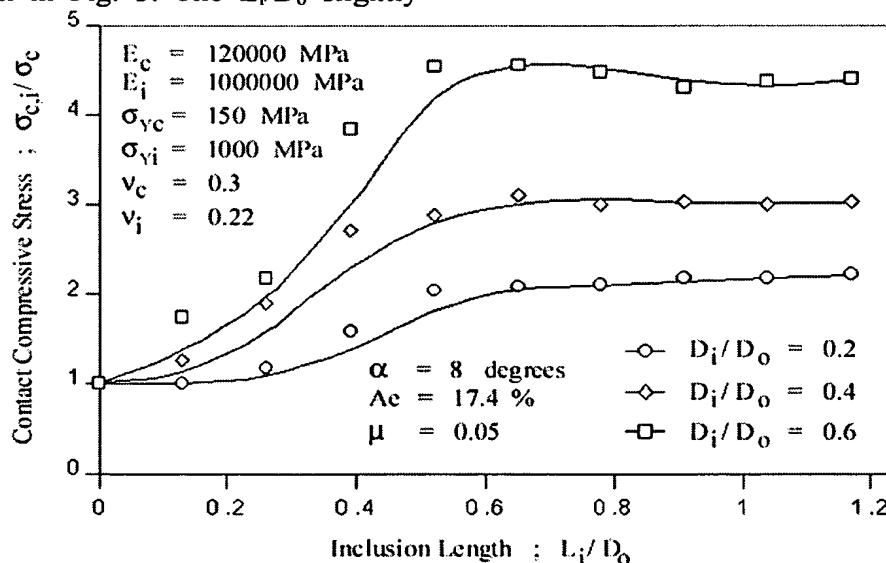


Fig. 3. Variations of contact compressive stress with the inclusion length.

length equals, and is longer than, 1.17 for inclusion sizes equaled to 0.4.

6. Wire breakage occurred when inclusion length equals, and is longer than, 0.39 for non-dimensional inclusion size equaled to 0.6.

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